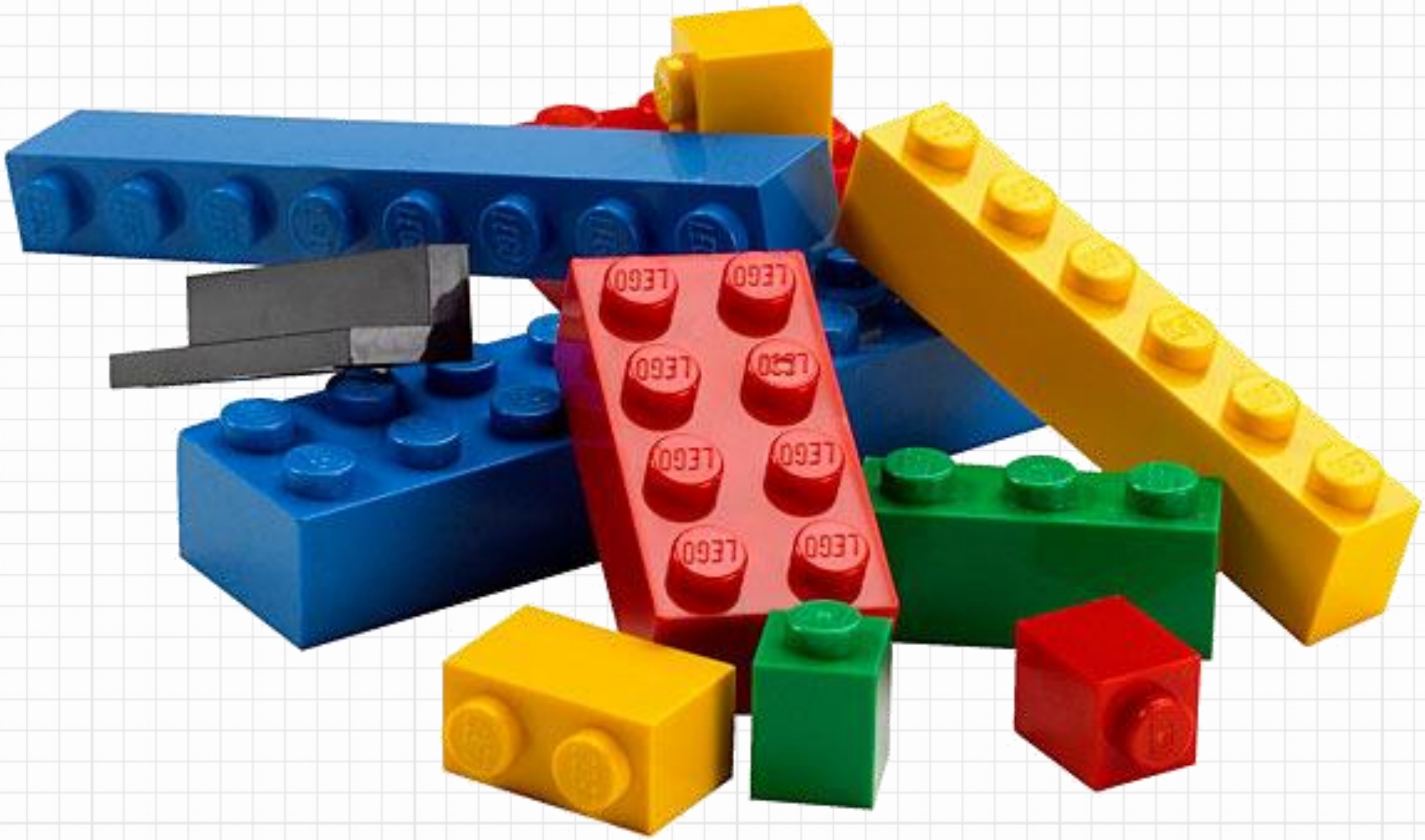
Modeling, Simulation and Deployment

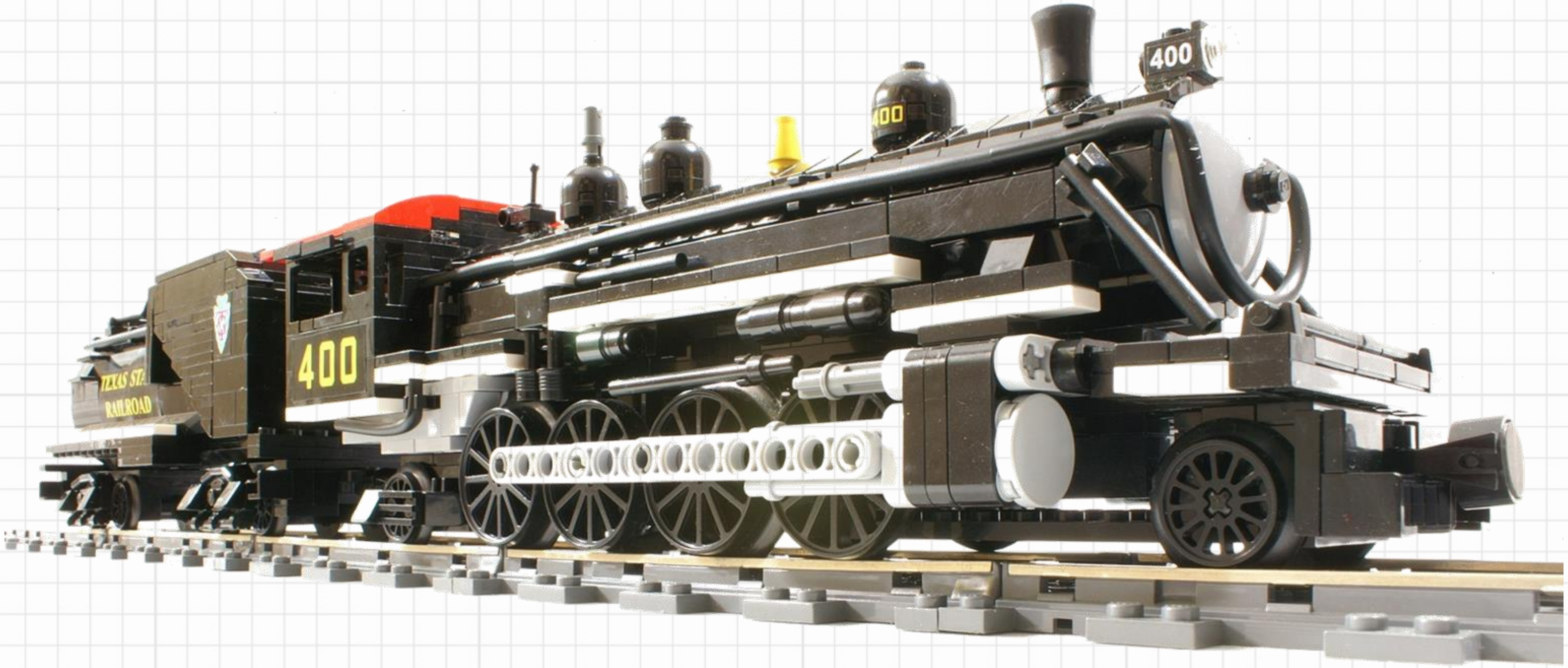
Dr. Michael Tiller
Xogeny

Modeling

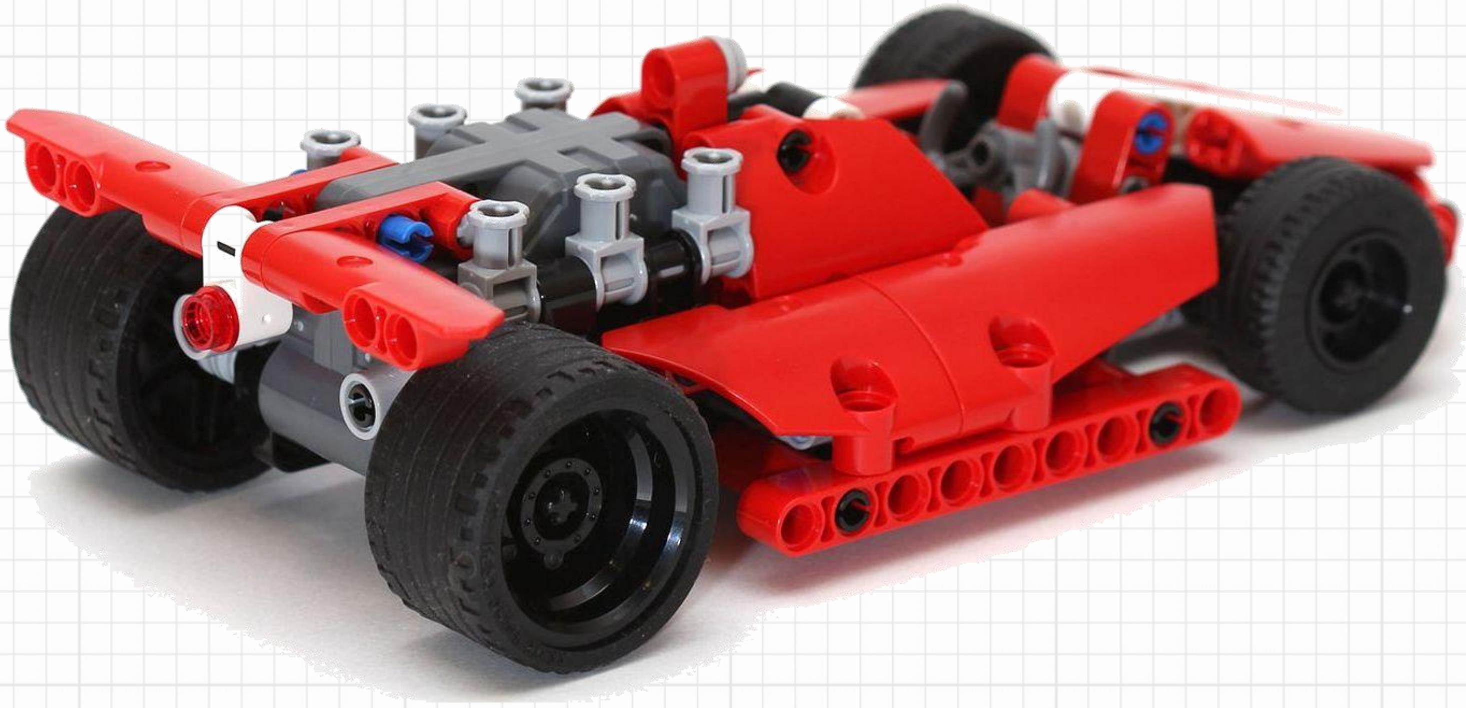
Modeling



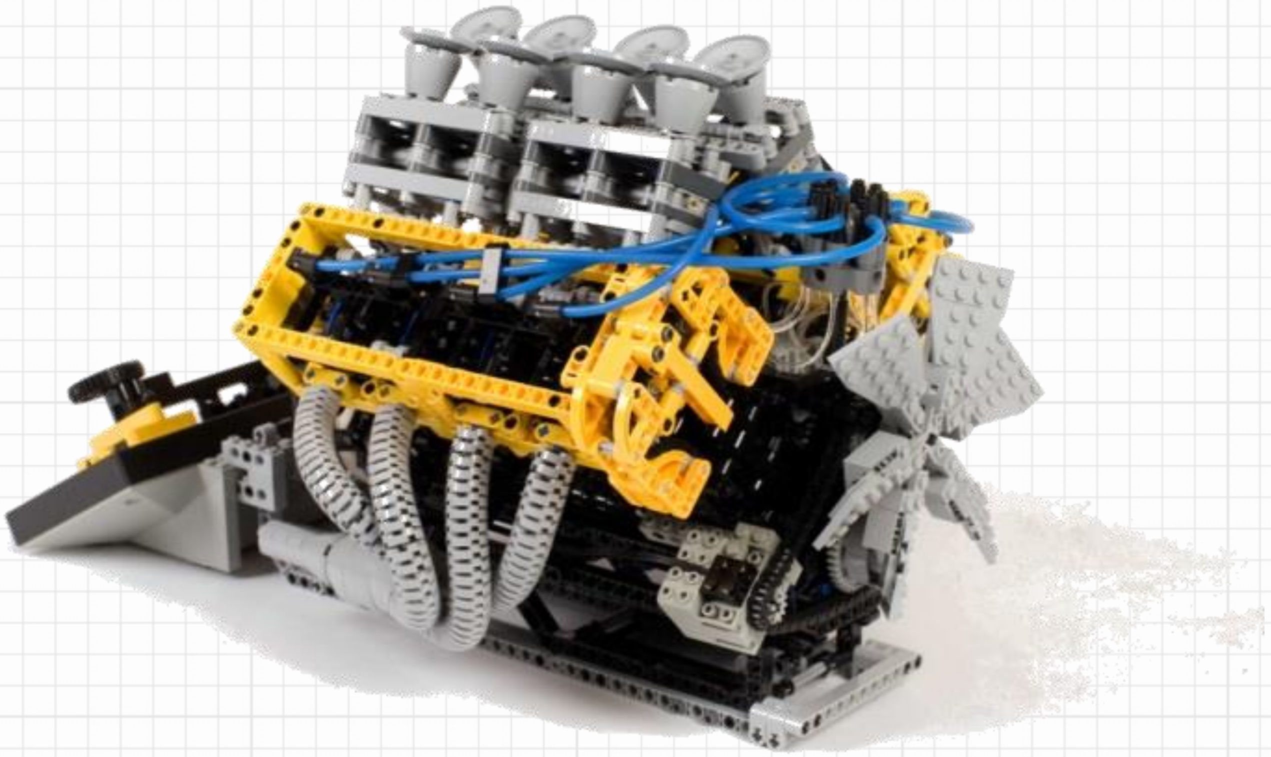
Modeling



Modeling



Modeling

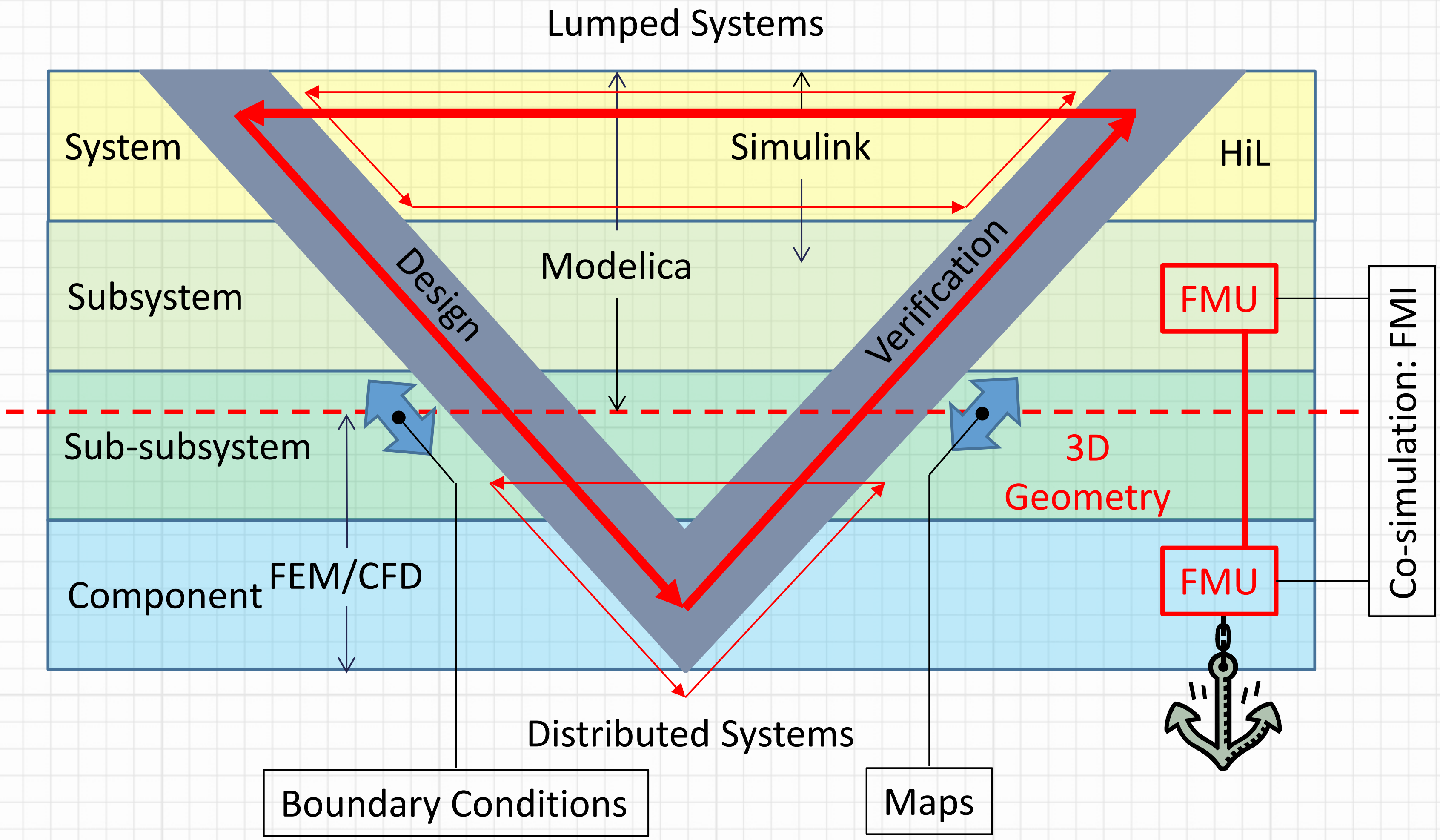


Modeling

Modeling

Am I at the wrong talk?

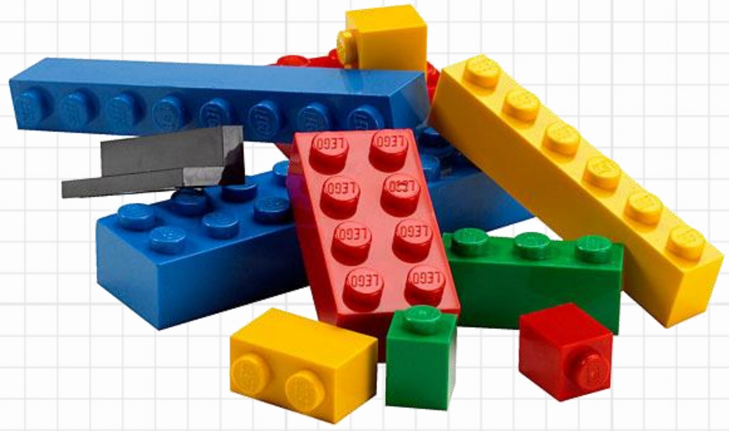
Modeling and “the V”



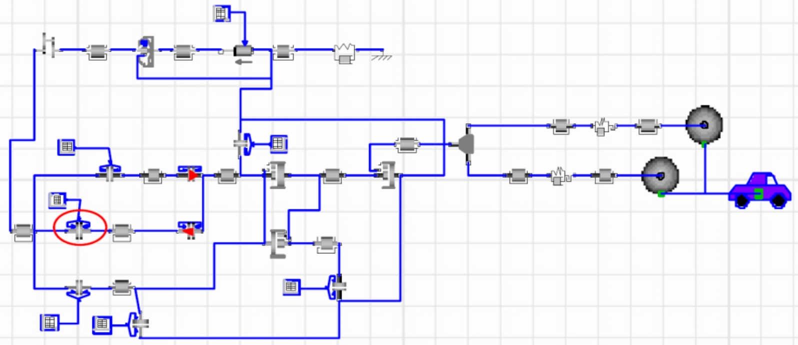
Modelica

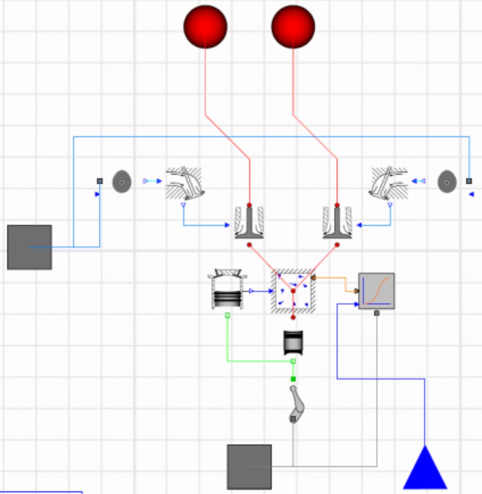
- Modelica is a modeling language that is:
  - Vendor-neutral
  - Multi-domain
  - Object-oriented
  - Multi-formalism
- Modelica is like LEGOs for building mathematical system models

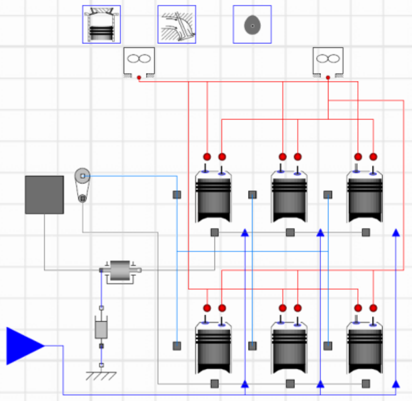
MODELICA =

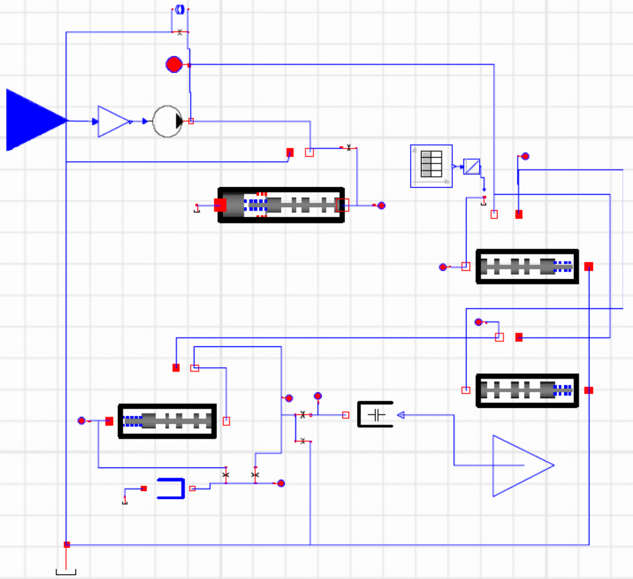


Modelica

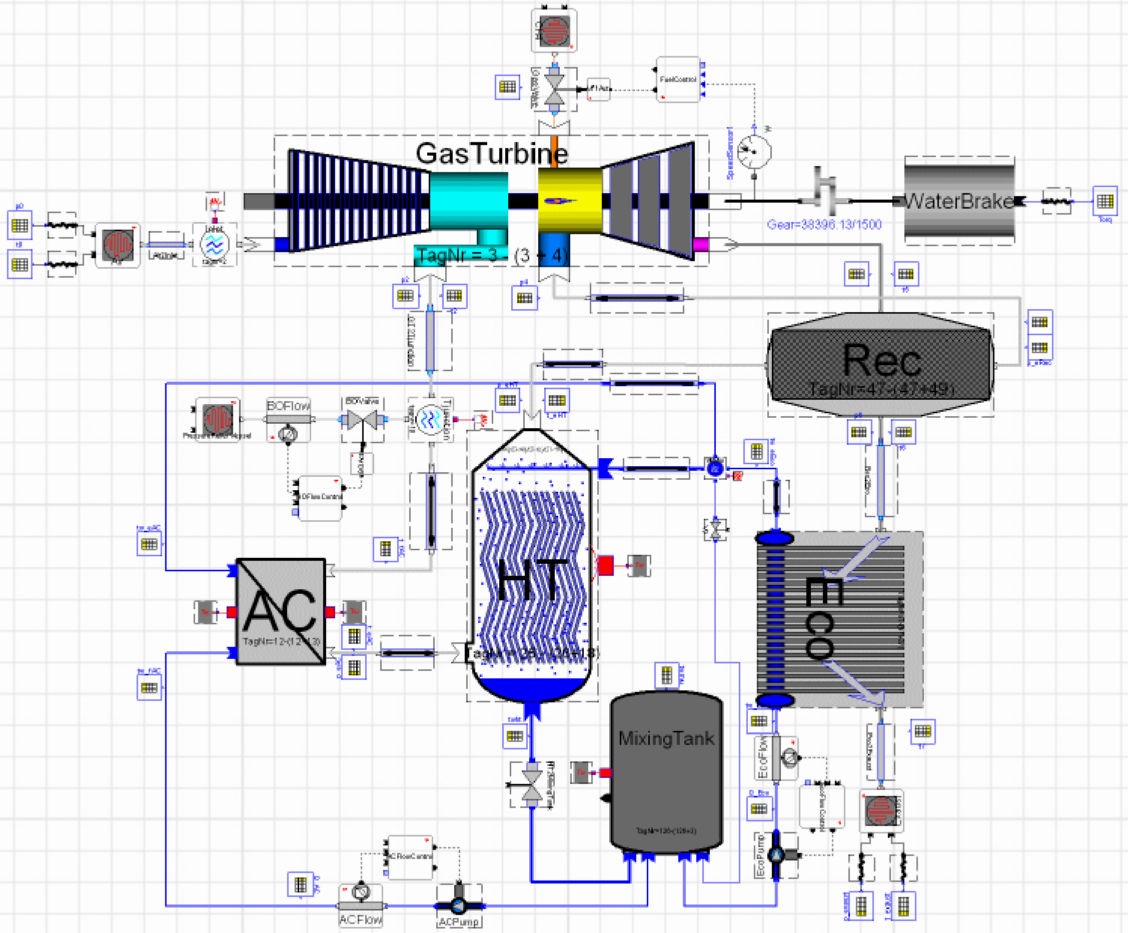




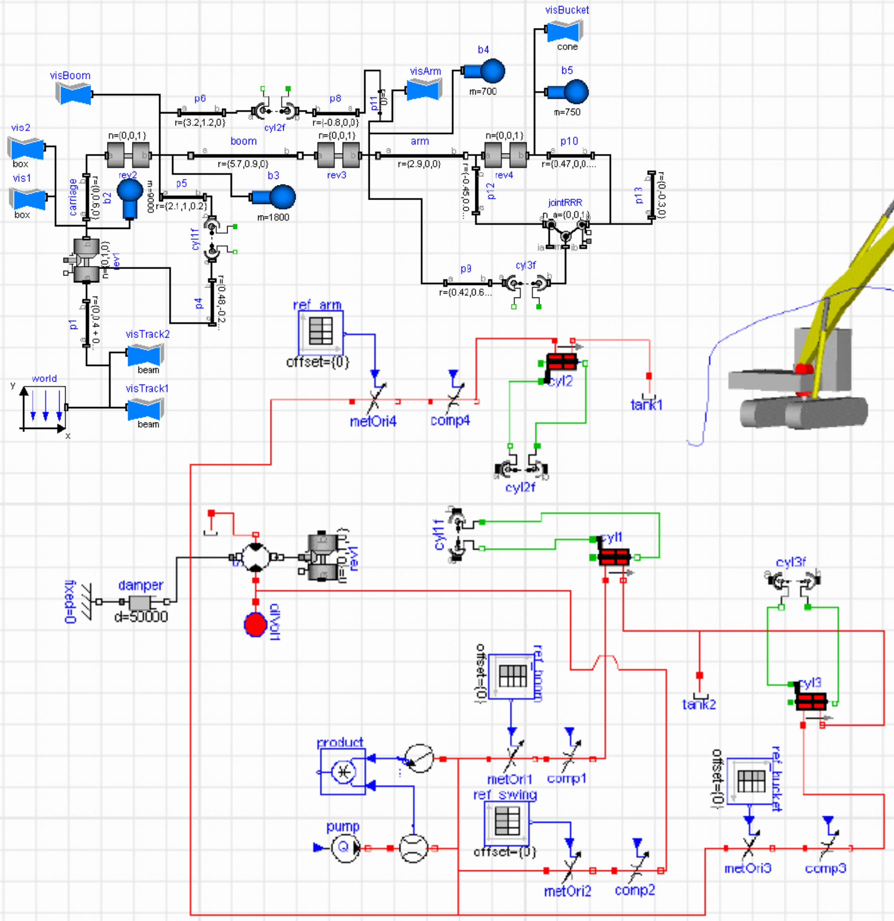




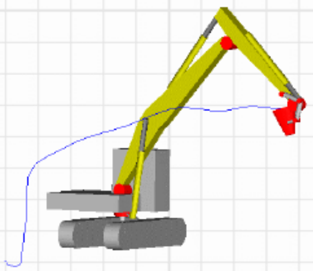
Modelica


GasTurbine
TagNr = 3 - (3 + 4)
WaterBrake
Gear=38396.13/1500
Rec
TagNr=47-(47+49)
BOFlow
BOValve
AC
TagNr=12-(12+13)
HT
Eco
MixingTank
EcoFlow
EcoPump
ACFlow
ACPump

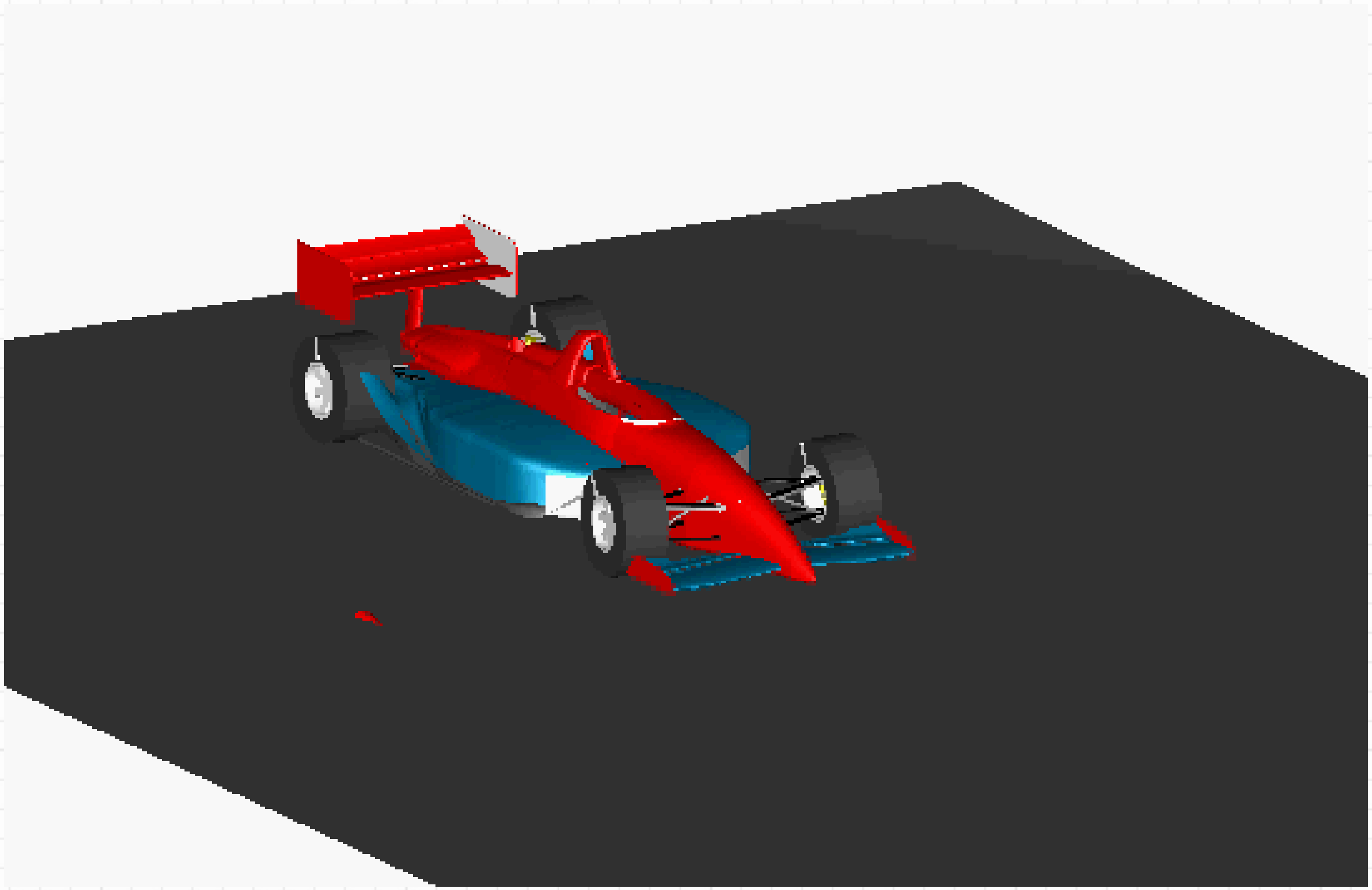
Modelica



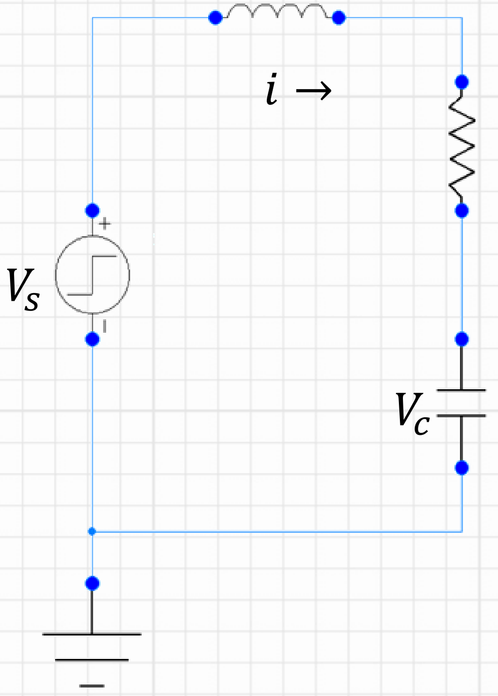
visBucket
cone
b4
m=700
b5
m=750
visBoom
visArm
p6
p8
cyl2f
p11
vis2
box
vis1
box
carriage
rev2
boom
b3
m=1800
rev3
arm
rev4
p10
p12
p13
jointRRR
p5
cyl1f
p4
p1
rev1
p9
cyl3f
visTrack2
beam
visTrack1
beam
world
ref_arm
offset={0}
metOri4
comp4
cyl2
tank1
cyl2f
cyl1f
cyl1
cyl3f
fixed=0
damper
d=50000
oilVol1
rev1
ref_boom
offset={0}
tank2
cyl3
product
metOri1
comp1
ref_swing
offset={0}
ref_bucket
offset={0}
pump
metOri2
comp2
metOri3
comp3

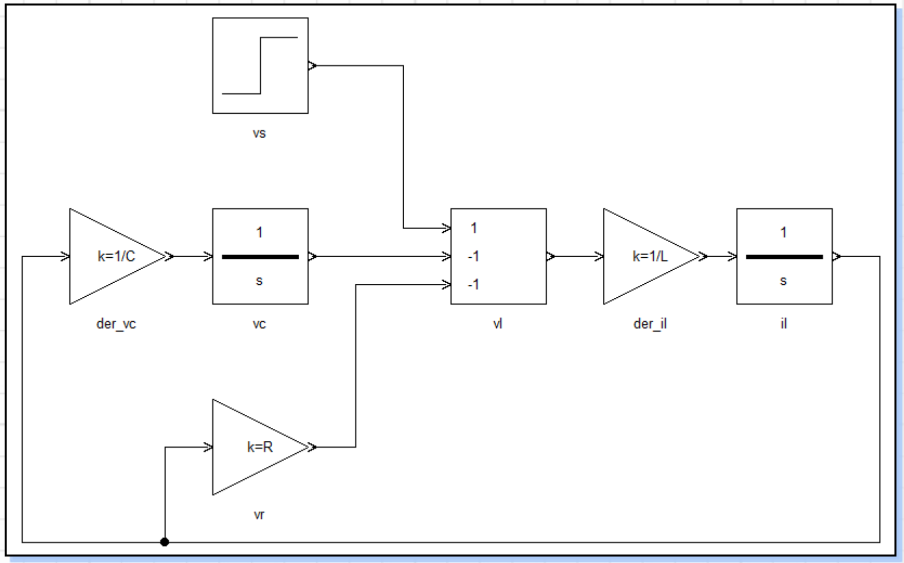


Modelica

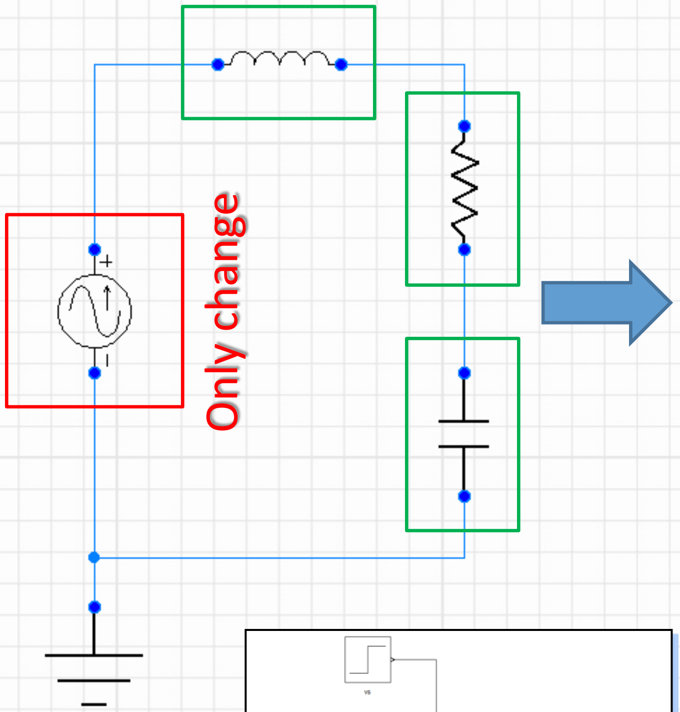


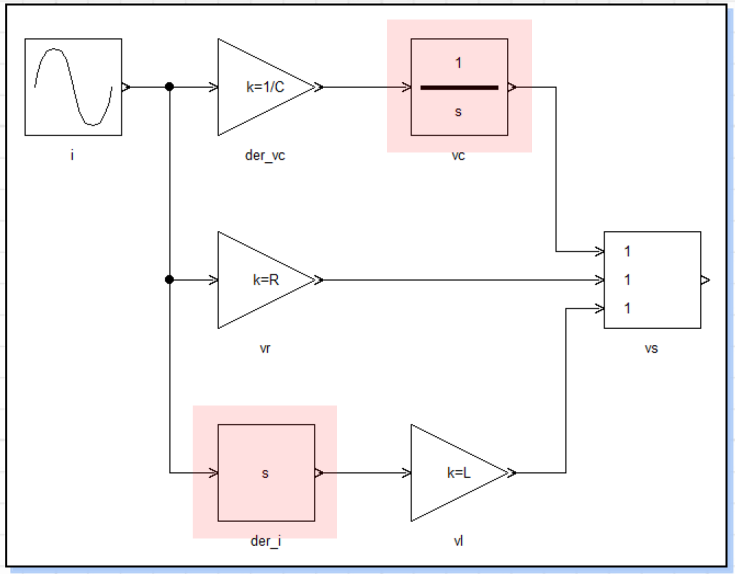
Acausal Modeling

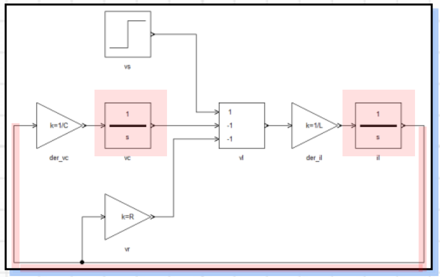




Flexibility







Only 1 state (vs. 2 previously)
No feedback loop
Differentiation block

Completely different model!

Learning vs. Doing

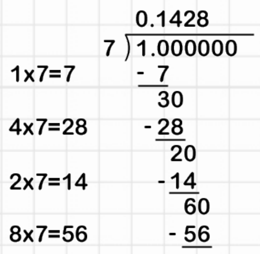
Block Diagrams

» Textbook equations have to be constantly reformulated depending on context.

» Different "blocks" with different combinations of inputs and outputs.

» Tedious, time-consuming and error prone.

» Long-division



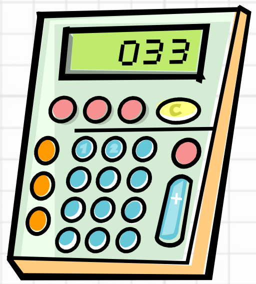
Acausal Modeling

» Textbook equations are captured in reusable object-oriented component models.

» A single component for all causalities (e.g. planetary gear).

» Fun, fast and automated (and efficient!)

» Calculator



DAEs

- » Natural way to describe physical behavior
  - > Multi-body systems (joint constraints)
  - > Fluid problems (ideal gas law)
  - > Easy to express many important idealizations (~~stiff springs~~)
- » Difficult to solve in a purely numerical way
  - > Consistent initial conditions
  - > High index DAEs
- » Preferred solution methods:
  - > Index reduction (Pantelides' algorithm)
  - > Dummy derivative method
  - > Turn DAE into ODEs (or index-1 DAEs)

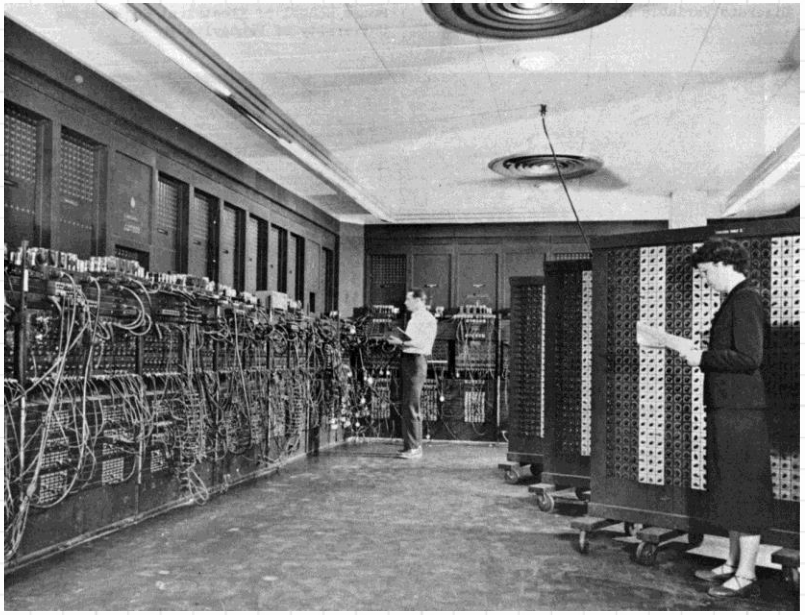
Possibilities

» Attraction of modeling is the landscape of infinite possibilities it creates.

Simulation

In the beginning…

» What were computers invented for?



ENIAC (circa 1947-1955)

“The Giant Brain”

Artillery Firing Tables

» Simulation is as old as computing itself.

Solution Method

» Originally, solution schemes (integration) was integrated with problem:

```
V = V + A*dt;
X = X + V*dt;
```

» Eventually, problem and solver were cleanly partitioned:

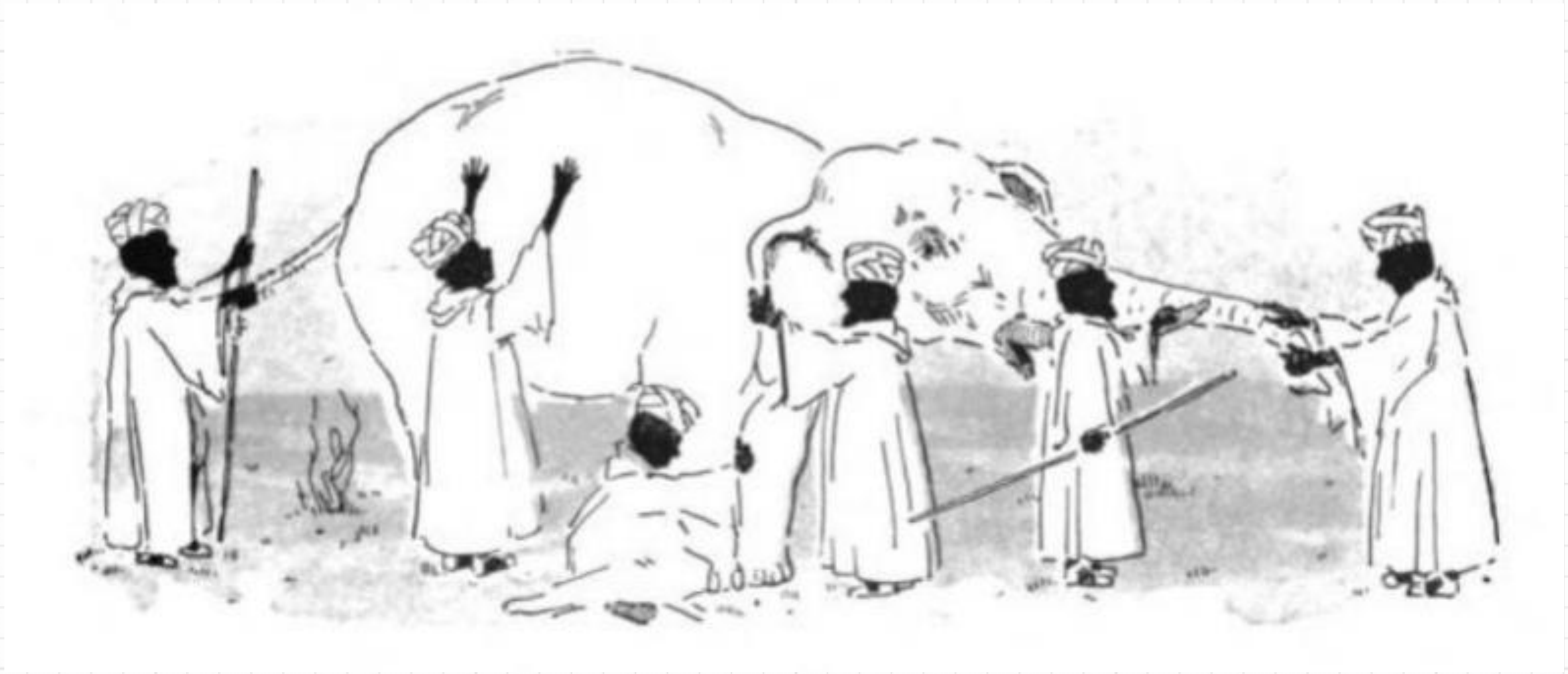
$$\dot{x}(t) = \boxed{f(x,u,t);}\ x_{n+1} = x_n + hf(t_n + \frac{h}{2}, x_n + \frac{hf(t_n, y_n)}{2})$$

» Performance:

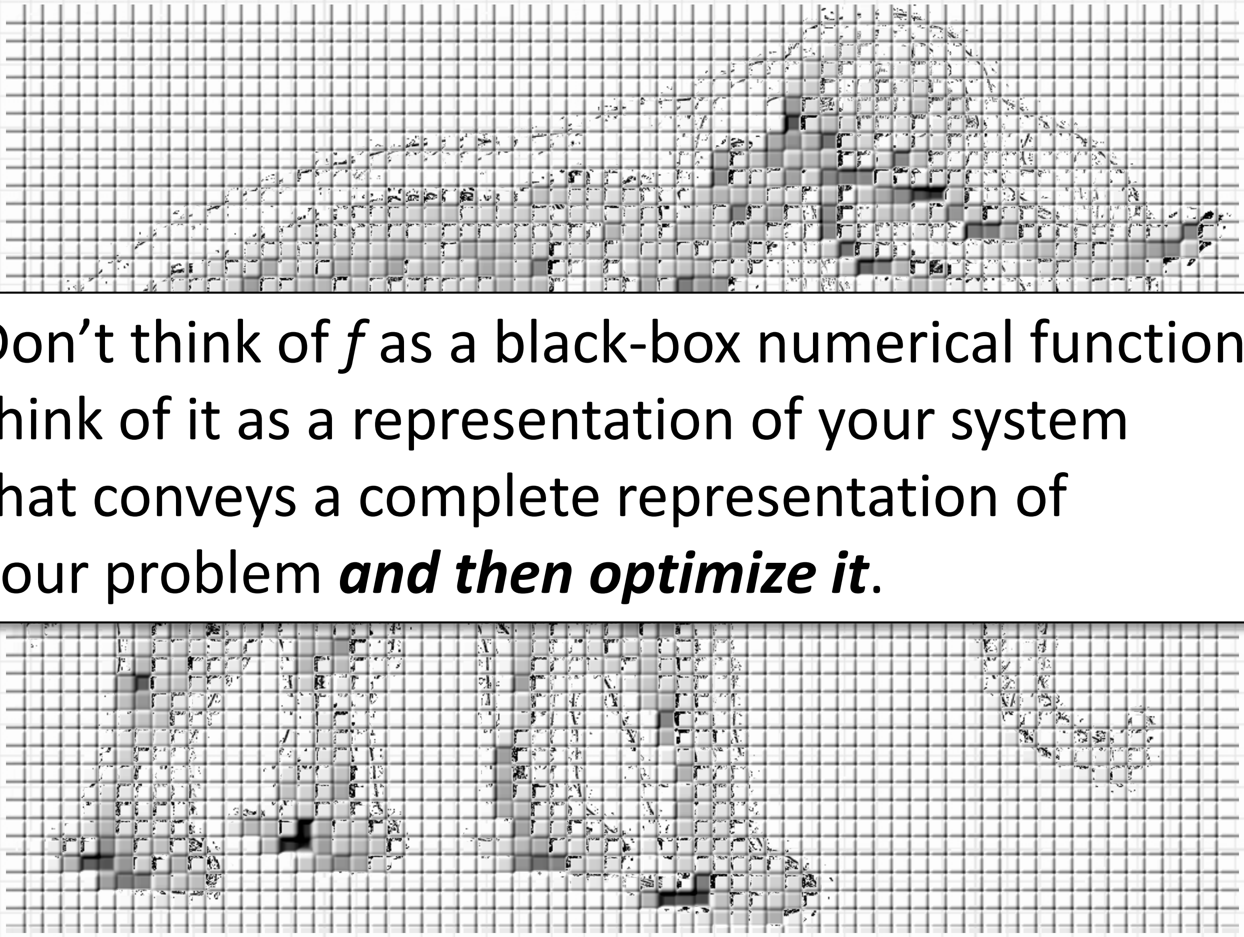
> $\underline{\text{(Cost of evaluation } f\text{)}} \times \underline{\text{(\# of times f is evaluated)}}$

Evaluation Costs

» The Six Blind Men and The Elephant



The Modeling Elephant



Don’t think of *f* as a black-box numerical function, think of it as a representation of your system that conveys a complete representation of your problem ***and then optimize it***.

I give you MORE numbers, you give me MORE numbers.

I give you a number, you give me a number.

Query the underlying structure

Symbolic Manipulation

- Umbrella topic for:
  - Equation sorting
  - Index reduction
  - State selection
  - Substitutions
  - Tearing

  $\left.\right\}$ Requires structural information
- Goal is not a symbolic/analytical solution
- Reduces the DAEs down to ODEs
  - More natural way to express behavior
  - Reuse established numerical solvers
  - Heavily optimize evaluation costs
- Opinion: it will be impossible for purely numerical tools to compete.

Generating Equations

$$\left.\begin{aligned}&step.n.v = resistor.n.v\\&resistor.n.v = inductor.n.v\\&inductor.n.v = capacitor.n.v\\&capacitor.n.v = ground.n.v\end{aligned}\right\} \leftarrow$$

Across variables (equated)

$$step.n.i + resistor.n.i + inductor.n.i + capacitor.n.i + ground.n.i = 0 \leftarrow$$

Through variables (summed)

$$step.p.v = resistor.p.v$$
$$resistor.p.v = inductor.p.v$$
$$inductor.p.v = capacitor.p.v$$
$$step.p.i + resistor.p.i + inductor.p.i + capacitor.p.i = 0$$

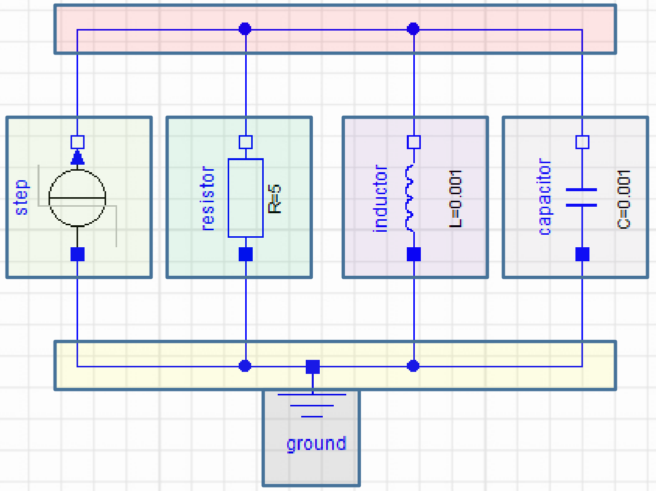
$$step.p.i + step.n.i = 0$$
$$step.p.i = f(t)$$

$$resistor.p.i + resistor.n.i = 0$$
$$resistor.p.i * resistor.R = resistor.p.v - resistor.n.v$$

$$inductor.p.i + inductor.n.i = 0$$
$$der(inductor.p.i) * inductor.L = inductor.p.v - industor.n.v$$

$$capacitor.p.i + capacitor.n.i = 0$$
$$capacitor.p.i = capacitor.C * [der(capacitor.p.v) - der(capacitor.n.v)]$$

$$ground.n.v = 0$$



Equation Structure

$$step.n.v = resistor.n.v$$

$$resistor.n.v = inductor.n.v$$

$$\underline{inductor.n.v} \Leftarrow \underline{capacitor.n.v}$$

$$\underline{capacitor.n.v} \Leftarrow \underline{ground.n.v}$$

$$step.n.i + resistor.n.i + inductor.n.i + capacitor.n.i + ground.n.i = 0$$

$$step.p.v = resistor.p.v$$

$$resistor.p.v = inductor.p.v$$

$$inductor.p.v = capacitor.p.v$$

$$step.p.i + resistor.p.i + inductor.p.i + capacitor.p.i = 0$$

$$step.p.i + step.n.i = 0$$

$$step.p.i = f(t)$$

$$resistor.p.i + resistor.n.i = 0$$

$$resistor.p.i * resistor.R = resistor.p.v - resistor.n.v$$

$$inductor.p.i + inductor.n.i = 0$$

$$der(inductor.p.i) * inductor.L = inductor.p.v - industor.n.v$$

$$capacitor.p.i + capacitor.n.i = 0$$

$$capacitor.p.i * capacitor.C = der(capacitor.p.v) - der(capacitor.n.v)$$

$$\underline{ground.n.v} \Leftarrow \underline{0}$$

Structure of Equations

$$\begin{bmatrix}
 & & & -1 & 1 & & & & & & & & & & & & & \\
 & & -1 & 1 & & & & & & & & & & & & & & \\
 & -1 & 1 & & & & & & & & & & & & & & & \\
-1 & 1 & & & & & & & & & & & & & & & & \\
 & & & & & & & & -1 & 1 & & & & & & & & \\
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 & & 1 & & & & & -1 & & & L & & & & & & & \\
 & & & & & & & & & & & & & & -1 & 1 & & \\
 & & & & & & & & & & & & & & -1/C & & 1 & \\
 & & & & & & & & & & & 1 & & 1 & & 1 & & 1 \\
1 & & & & & & & & & & & & & & & & &
\end{bmatrix}$$

Sorted Structure

$$\begin{Bmatrix} ground.n.v \\ capacitor.n.v \\ inductor.n.v \\ resistor.n.v \\ step.n.v \\ step.p.i \\ step.n.i \\ inductor.p.v \\ resistor.p.v \\ step.p.v \\ der(inductor.p.i) \\ inductor.n.i \\ resistor.p.i \\ resistor.n.i \\ capacitor.p.i \\ capacitor.n.i \\ der(capacitor.p.v) \\ ground.n.i \end{Bmatrix} := \begin{Bmatrix} 0 \\ ground.n.v \\ capacitor.n.v \\ inductor.n.v \\ resistor.n.v \\ f(t) \\ -step.p.i \\ capacitor.p.v \\ inductor.p.v \\ resistor.p.v \\ (inductor.p.i - inductor.n.v)/inductor.L \\ -inductor.p.i \\ (resistor.p.v - resistor.n.v)/resistor.R \\ -resistor.p.i \\ -step.p.i - resistor.p.i - inductor.p.i \\ -capacitor.p.i \\ capacitor.p.i/capacitor.C \\ -step.n.i - resistor.n.i - inductor.n.i - capacitor.n.i \end{Bmatrix}$$

$$\begin{bmatrix}
1 &&&&&&&&&&&&&&&&& \\
-1 & 1 &&&&&&&&&&&&&&&& \\
& -1 & 1 &&&&&&&&&&&&&&& \\
&& -1 & 1 &&&&&&&&&&&&&& \\
&&&& 1 &&&&&&&&&&&&& \\
&&&& 1 & 1 &&&&&&&&&&&& \\
&&&&&& 1 &&&&&&&&&&& \\
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&&&&&&&&&& 1 & 1 &&&&&& \\
&&& \frac{1}{R} &&&&& -\frac{1}{R} &&&& 1 &&&&& \\
&&&&&&&&&&&& 1 & 1 &&&& \\
&&&&& 1 &&&&&&& 1 && 1 &&& \\
&&&&&&&&&&&&&& 1 & 1 && \\
&&&&&&&&&&&&&& -\frac{1}{C} && 1 & \\
&&&&&& 1 &&&&& 1 && 1 && 1 && 1
\end{bmatrix}$$

Functional Mockup Interface (FMI)

FMI

- Functional Mockup Interface (FMI)
- Initiated by Daimler as an industry wide and vendor neutral alternative to (MathWorks) S-functions.
- Initially funded by EU. Eventually became an official Modelica Association project.
- A way to exchange **compiled** models
  - Not really a modeling technology
  - Limited “composability”
- FMI 2.0-RC1 just released
  - Support for discrete states
  - Algebraic loops during events and initialization

FMU

- Functional Mockup Unit – FMU
- Pre-compiled collection of files:
  - Binaries (for various platforms)
  - Source code (in provided)
  - Resources (data files, etc)
  - Documentation
  - Model Description (XML file)
- FMUs are instantiated
  - Potentially multiple instances in same simulation
  - Can be formulated for “Model Exchange” or “Co-simulation”

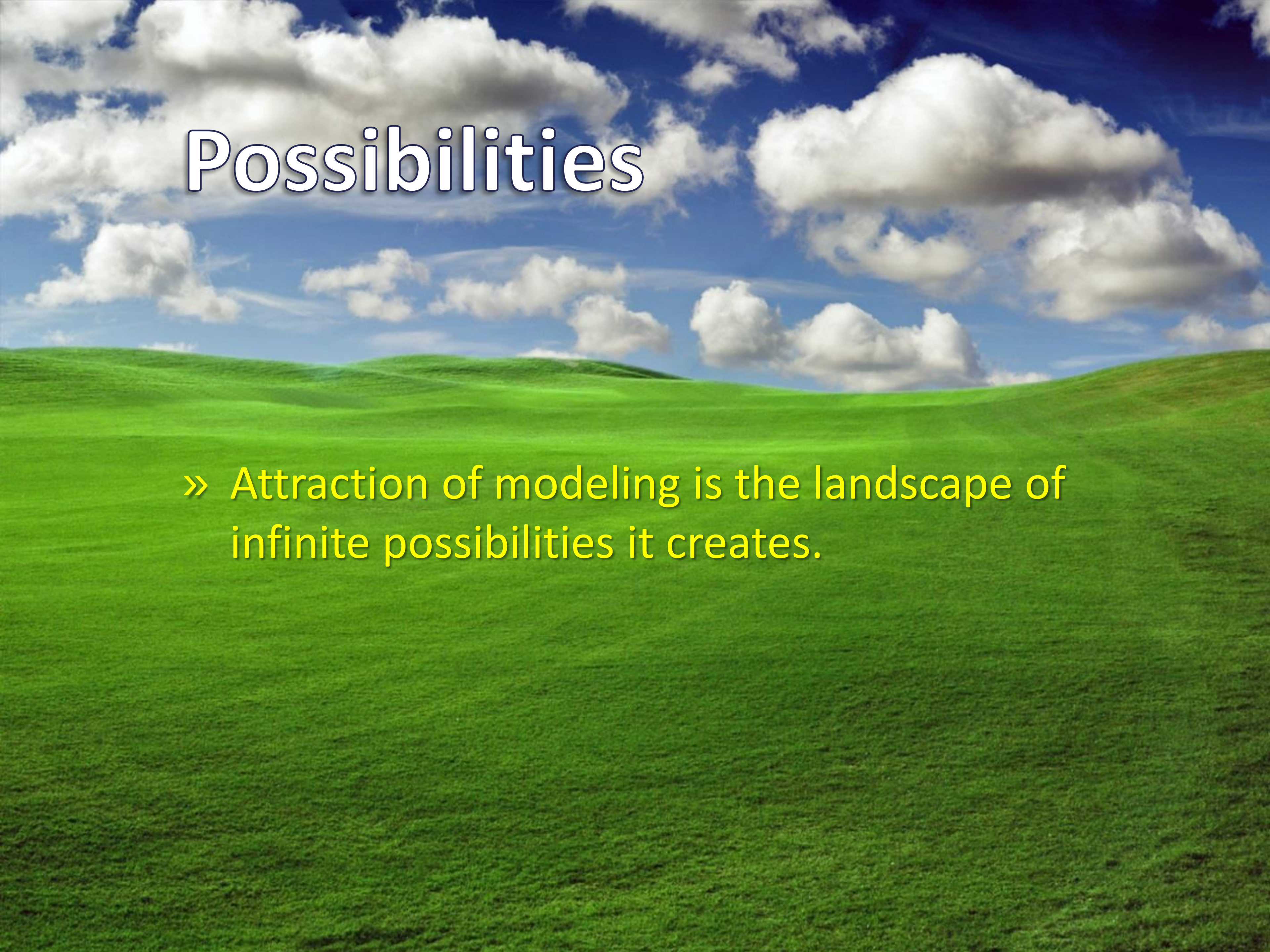
Architectural Shifts

- » Reaching limitations of classic Von Neumann architecture (CPU+memory).
- » Multi-core machines and cloud computer resources are becoming increasingly common.
- » Simulation is typically heavily sequential
- » Exploiting future computing resources:
  - > Thinking more about parallel computations
  - > Loosely coupled analyses
  - > Cheaper computing and timing driving analyses like optimization, monte-carlo and other parallelizable types of analysis
  - > Model reduction could become more cost effective

FMQ

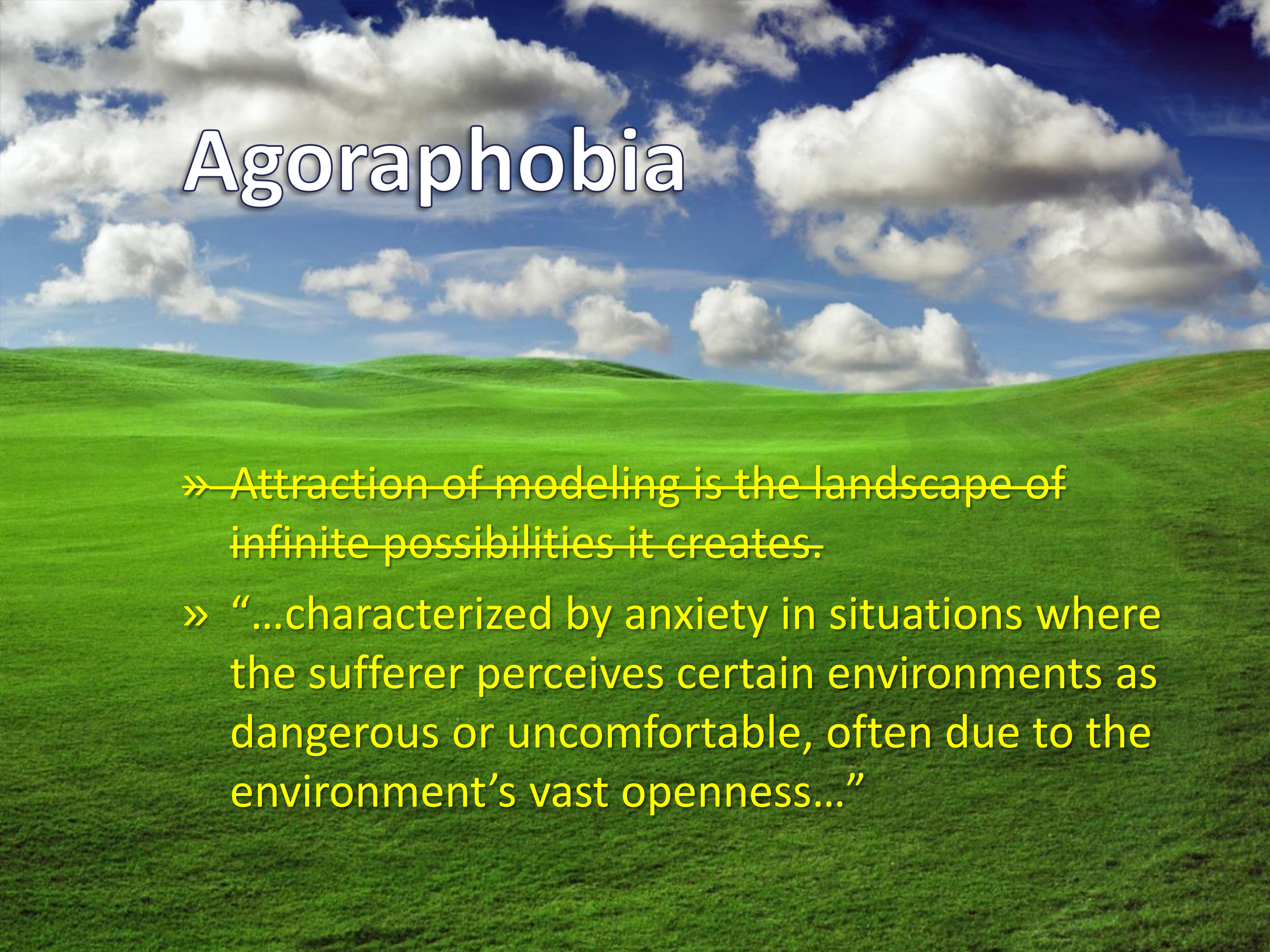
- Xogeny proprietary platform
- Platform for running FMI compliant models "in the cloud"
- Inspiration came from dynamic programming application where desktop resources weren't sufficient.
- Easy path to model reduction, Monte-Carlo analysis, etc.
- Wraps analyses in data management framework for persisting input and output data.

Deployment



Possibilities

» Attraction of modeling is the landscape of infinite possibilities it creates.



Agoraphobia

- ~~Attraction of modeling is the landscape of infinite possibilities it creates.~~
- "…characterized by anxiety in situations where the sufferer perceives certain environments as dangerous or uncomfortable, often due to the environment's vast openness…"

Infinite Possibilities

User Experience

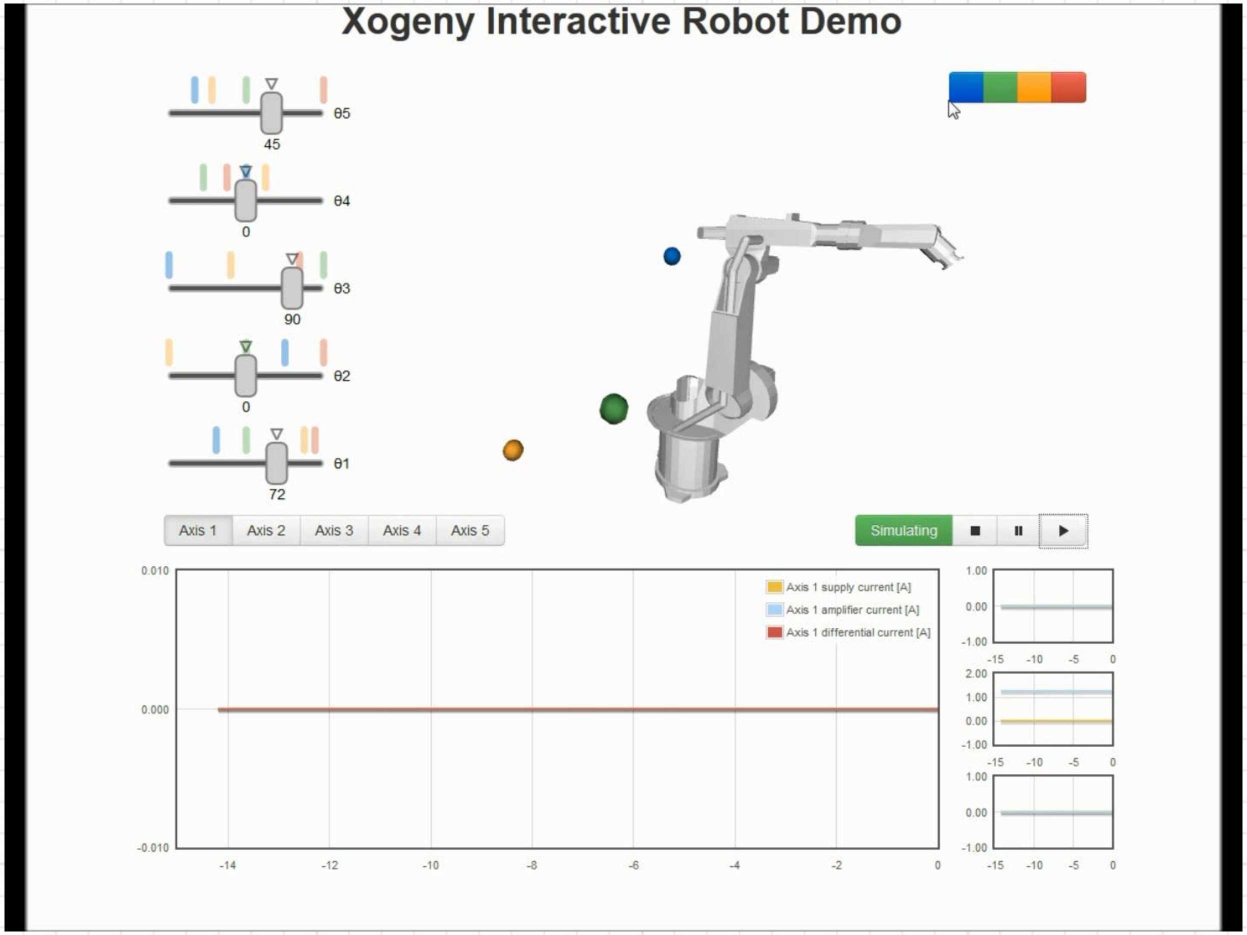
- It is worth the effort to organize features and capabilities around achieving a great user experience.

Model → Application

- Important to understand the business questions that need answering.
  - Do you need one application or many?
- Models are the "functions" to capture non-trivial relationships.
  - Can be recombined in different ways depending on the use case.
- Applications need to provide a clear path from models to questions/solutions.
- Software architectures often tend toward monolithic applications.
- Xogeny applications heavily leverage declarative representations and code generation.
  - Don't write applications, write programs that write applications.

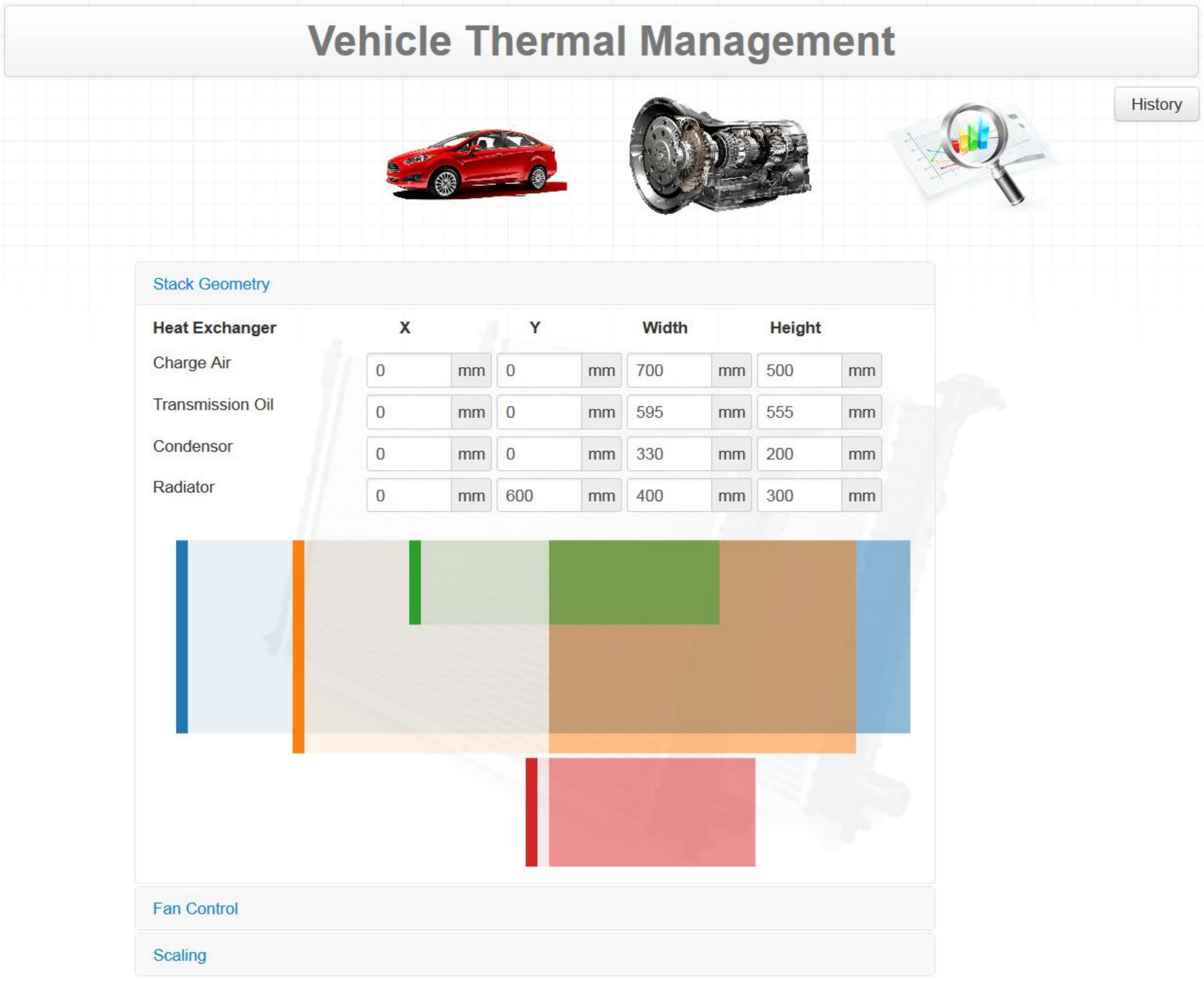
Web-Based Analyses

Interactivity



Xogeny Interactive Robot Demo
θ5
45
θ4
0
θ3
90
θ2
0
θ1
72
Axis 1
Axis 2
Axis 3
Axis 4
Axis 5
Simulating
Axis 1 supply current [A]
Axis 1 amplifier current [A]
Axis 1 differential current [A]

Turnkey Systems



Vehicle Thermal Management

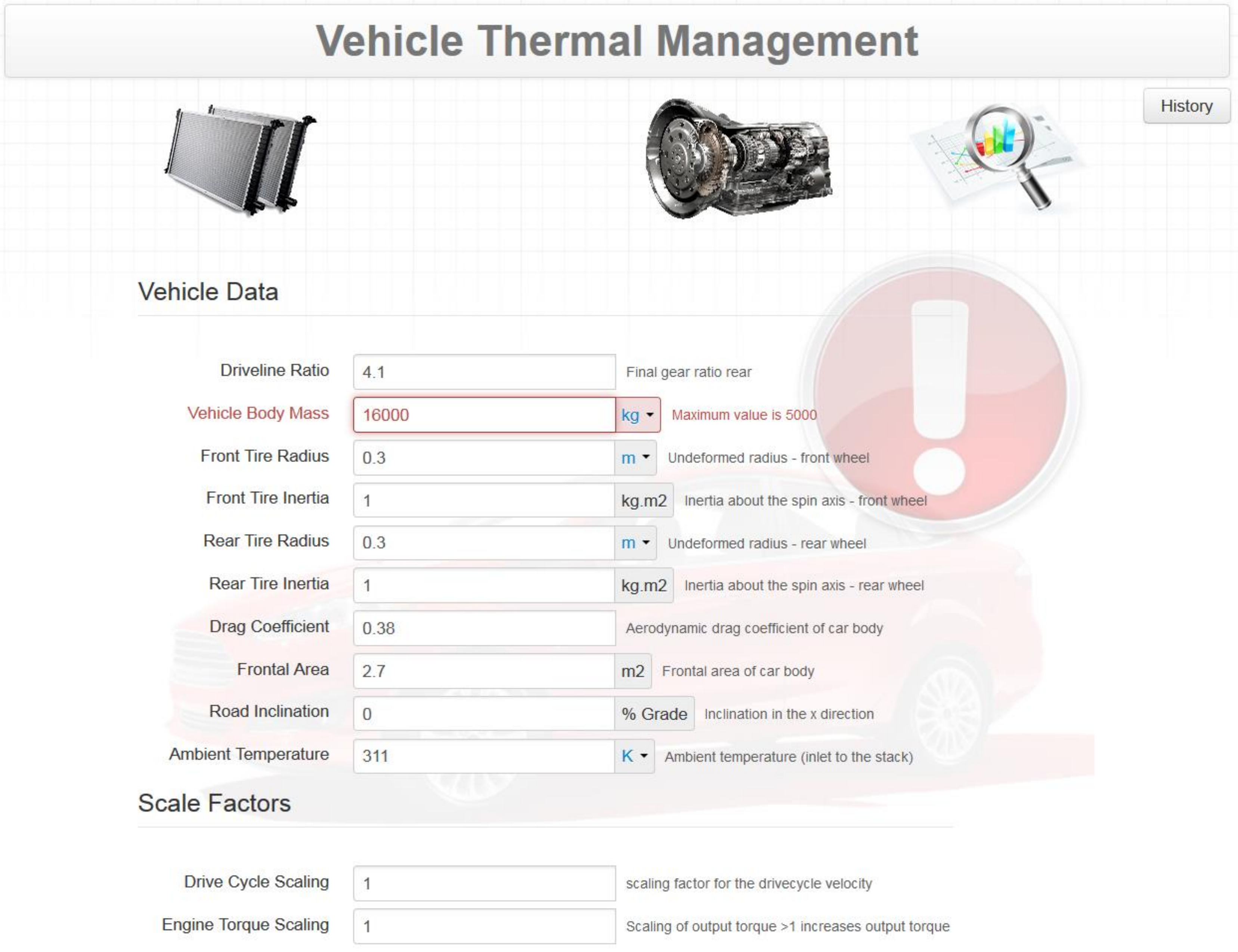
History

Stack Geometry

Heat Exchanger	X	Y	Width	Height
Charge Air	0 mm	0 mm	700 mm	500 mm
Transmission Oil	0 mm	0 mm	595 mm	555 mm
Condensor	0 mm	0 mm	330 mm	200 mm
Radiator	0 mm	600 mm	400 mm	300 mm

Fan Control

Scaling



Vehicle Thermal Management

Vehicle Data

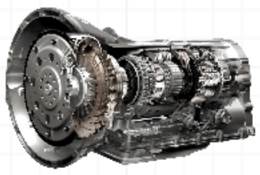
Driveline Ratio	4.1		Final gear ratio rear
Vehicle Body Mass	16000	kg	Maximum value is 5000
Front Tire Radius	0.3	m	Undeformed radius - front wheel
Front Tire Inertia	1	kg.m2	Inertia about the spin axis - front wheel
Rear Tire Radius	0.3	m	Undeformed radius - rear wheel
Rear Tire Inertia	1	kg.m2	Inertia about the spin axis - rear wheel
Drag Coefficient	0.38		Aerodynamic drag coefficient of car body
Frontal Area	2.7	m2	Frontal area of car body
Road Inclination	0	% Grade	Inclination in the x direction
Ambient Temperature	311	K	Ambient temperature (inlet to the stack)

Scale Factors

Drive Cycle Scaling	1	scaling factor for the drivecycle velocity
Engine Torque Scaling	1	Scaling of output torque >1 increases output torque

Vehicle Thermal Management

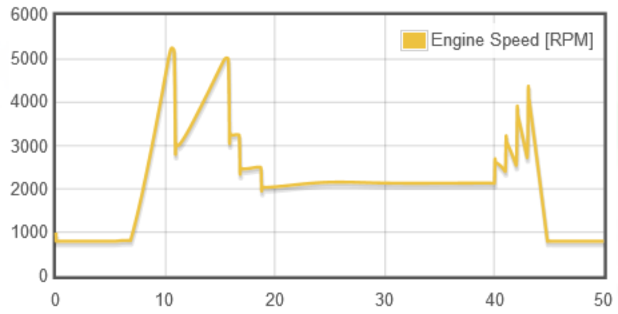
History

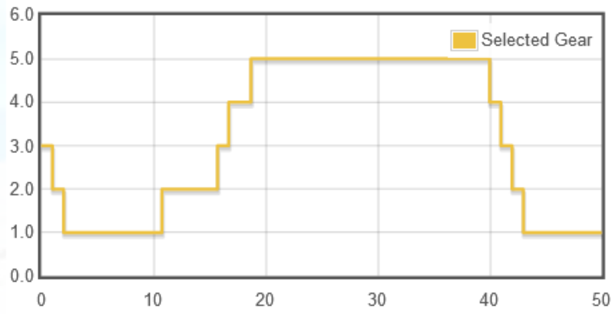


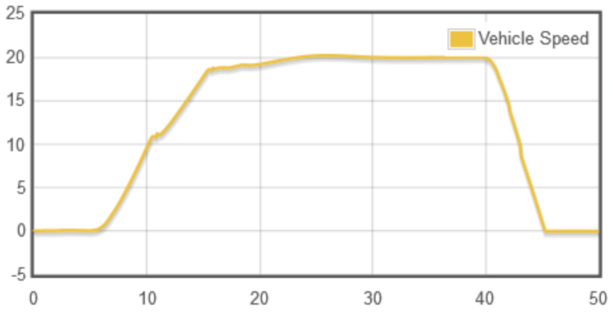
Temperatures

Drive Cycle

Drive Cycle







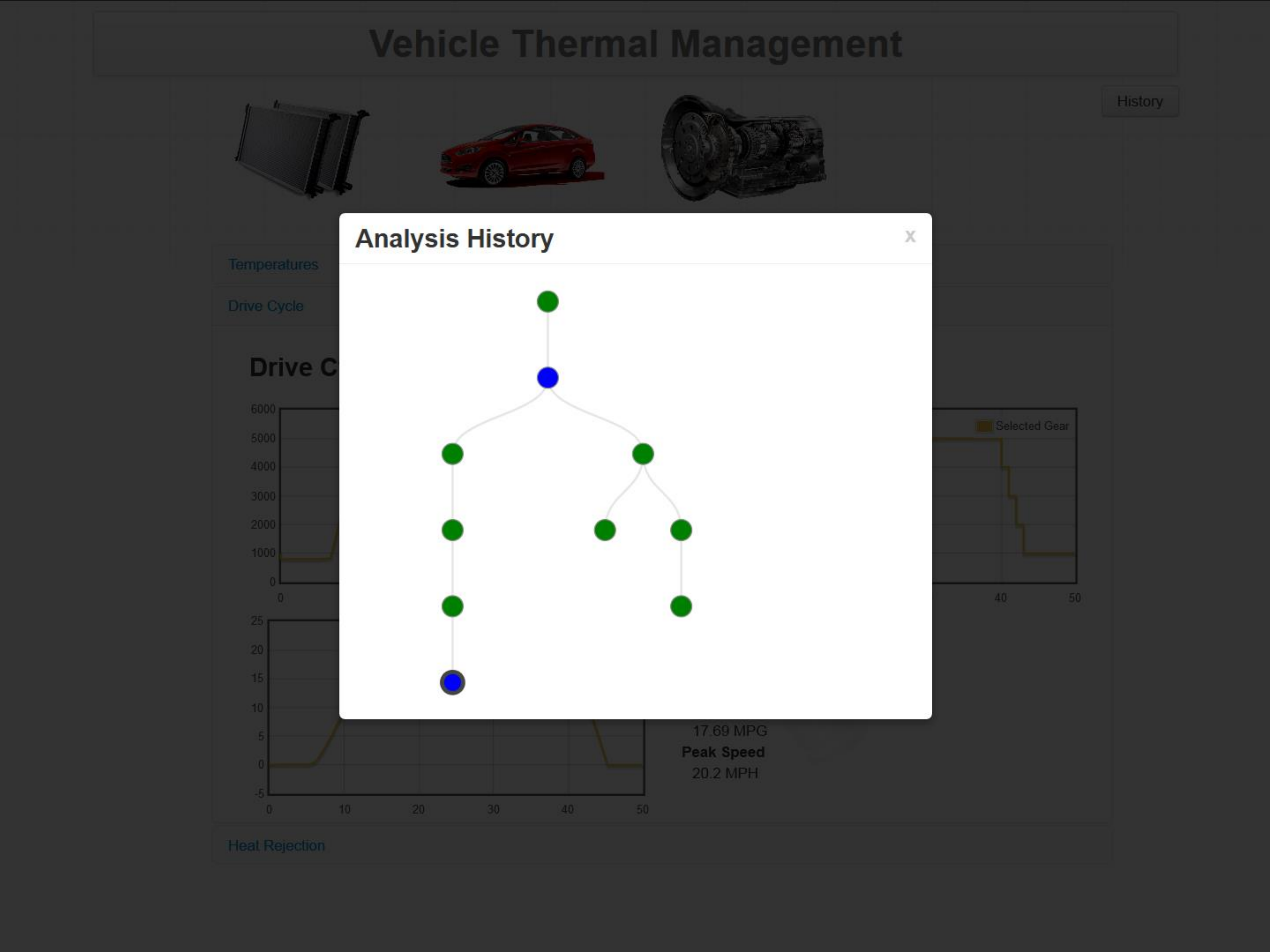
Statistics

Cycle Duration
50.0 seconds

Fuel Economy
17.69 MPG

Peak Speed
20.2 MPH

Heat Rejection



17.69 MPG

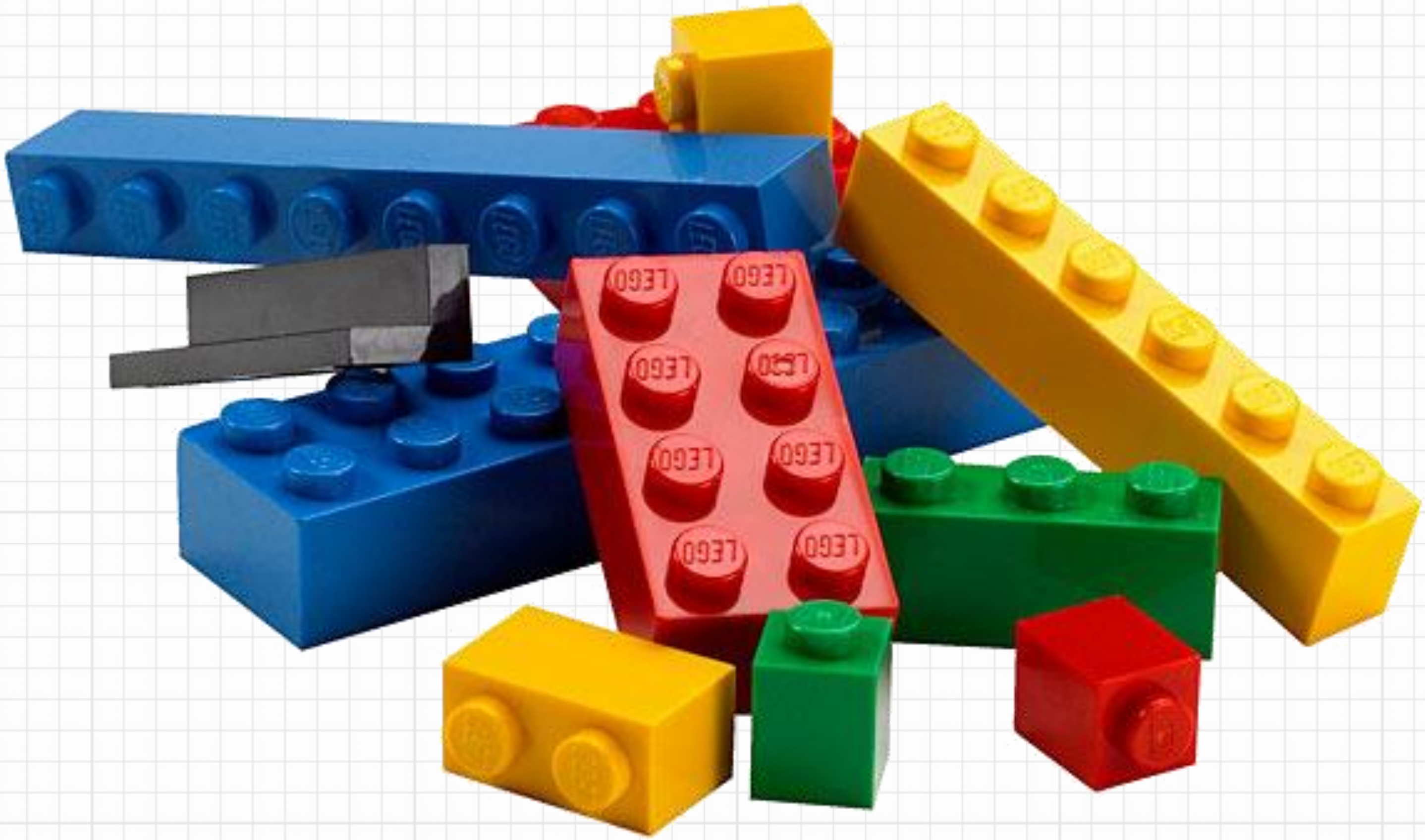
Peak Speed

20.2 MPH

Conclusions

- » Increasing pressure to connect CAD, CAE, requirements and system simulation.
- » Lots of compelling technologies out there that are not being leveraged.
  - > Competitive advantage in breaking away from legacy and capitalizing on these opportunities.
- » Highlight the value of modeling by making it accessible to everybody.
- » Exciting time for system simulation…

What Will You Build Today?



Questions?